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太阳风中离子束流与电磁离子回旋波的相互作用

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电磁离子回旋波是指频率低于或者接近离子回旋频率的电磁波, 其存在左旋和右旋两种偏振状态. 通过回旋共振相互作用, 电磁离子回旋波能直接与粒子发生能量交换, 对太阳风等离子体加热和加速等能化现象起着重要作用. 然而, 太阳风中电磁离子回旋波的激发机制及其波粒相互作用尚未完全清楚. 本学位论文深入、系统地研究了太阳风等离子体环境下离子束流对电磁离子回旋波激发机制的影响及其波粒相互作用, 为进一步理解与解释太阳风中微观等离子体物理过程、扰动的物理本质以及粒子能化现象等物理问题提供良好的理论依据.

首先, 介绍电磁离子回旋波的双流体和动力论的理论模型、波动特性、太阳风中电磁离子回旋波的观测特征、离子束流的观测特征、电磁离子回旋波的激发机制及其波粒相互作用.

其次, 研究在质子和电子束流激发离子回旋波情形下, 比较了反应和动力学不稳定性的相对重要性, 并讨论这两种不稳定性对太阳风回旋波激发机制的影响. 对于质子束流激发离子回旋波的情形, 结果显示: 动力学不稳定性存在较低的速度阈值$v_{\rm bi} \sim v_{\rm A}$ (其中$v_{\rm bi}$和$v_{\rm A}$分别表示质子束流的漂移速度和当地阿尔芬速度), 当$v_{\rm bi} > 2v_{\rm A}$时, 反应不稳定性将变得更加重要. 当质子束流速度满足$1 < v_{\rm bi}/v_{\rm A} < 2.5$时动力学不稳定性生长率最大, 这意味着在太阳风中即使质子束流的漂移速度很低, 动力学不稳定性依然能有效激发离子回旋波. 对于电子束流激发离子回旋波的情形, 结果显示: 动力学不稳定性的生长率小于或等于零, 意味着电子束流不能激发动力学不稳定性. 当电子束流的漂移速度远大于当地阿尔芬速度时($v_{\rm be} > 70v_{\rm A}$), 反应不稳定性能有效激发离子回旋波.

再次, 鉴于太阳风中α粒子的普遍性和重要性, 我们研究α粒子对电磁离子回旋波激发机制的影响. 结果表明: 电磁离子回旋波的实频、生长率和不稳定性阈值敏感依赖于α粒子的漂移速度和密度. 随着α粒子的漂移速度增加, 离子回旋波和磁声波的生长率先减少后增加, 且对离子回旋波影响更显著. 对比太阳风观测, 质子束流的漂移速度通常小于或者接近理论预测的回旋波速度阈值, 这暗示着太阳风中离子回旋和磁声不稳定性可以有效束缚质子束流的漂移速度.

最后, 为了进一步研究太阳风中质子束流的减速机制与演化过程, 我们研究斜离子回旋波和平行磁声波对质子束流演化的影响, 并考虑非线性波粒相互作用对束流减速的影响, 从而建立太阳风质子束流演化的物理模型. 结果表明: 斜离子回旋波和平行磁声波存在不同的不稳定性激发区间. 当电子等离子体热压磁压比满足$\beta_{\rm e} < \beta_{\rm e}^{\rm c} \sim 0.5$时, 斜离子回旋波能有效地激发, 而当$\beta_{\rm e} > \beta_{\rm e}^{\rm c}$时, 平行磁声波变得更加重要, 其中$\beta_{\rm e}^{\rm c}$为临界电子等离子体热压磁压比. 当太阳风从太阳往外传播时, 质子束流能有效激发斜离子回旋波, 波的激发导致质子束流的漂移速度下降, 使其低于斜离子回旋波的速度阈值; 当太阳风传播至0.55 au以外时, 平行磁声波被有效激发, 导致质子束流的漂移速度低于平行磁声波的速度阈值. 此外, 非线性波粒相互作用导致束流漂移速度进一步降低至$v_{\rm bi}/v_{\rm A} \sim 1.2$. 因此, 非线性波粒相互作用能解释太阳风中部分质子束流的漂移速度接近或稍大于当地阿尔芬速度的观测结果, 这可能对理

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解太阳风中质子束流的减速机制和演化过程有重要作用.

Interaction between Ion Beams and Electromagnetic Ion-Cyclotron Waves in the Solar Wind

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Electromagnetic ion cyclotron wave (EMICW) is a kind of electromagnetic wave whose frequency is lower than or close to the ion cyclotron frequency, and it has two polarization states of left-handed and right-handed. Due to the ion cyclotron resonance, EMICWs can exchange energy with particles directly, which is believed to play an important role in the energization of plasma particles in the solar wind. However, the excitation mechanism of EMICWs and its wave-particle interaction in the solar wind have not fully been understood. In this dissertation, we systematically investigate the influence of ion beams on the generation of EMICWs and its wave-particle interaction in the solar wind plasma environment. The results presented in this dissertation provide a good theoretical basis for further understanding the microscopic plasma process in the solar wind and the physical nature of disturbances as well as the energization phenomena of plasma particles.

Firstly, we introduce the two-fluid and kinetic models of EMICWs, wave properties, observation characteristics of EMICWs in solar wind and ion beams, generation mechanisms of EMICWs and its wave-particle interaction.

Secondly, in the case of ion cyclotron waves (ICWs) excited by proton and electron beams, the relative importance of reactive and kinetic instabilities is compared. The effects of these instabilities on the formation and excitation of ICWs in the solar wind are briefly discussed. In the case of ICWs driven by proton beams, the results show that the kinetic instability has a lower velocity threshold $v_{\rm bi} \sim v_{\rm A}$ (where $v_{\rm bi}$ and $v_{\rm A}$ represent the proton-beam drift velocity and the local Alfvén velocity, respectively), but the reactive instability becomes dominant as soon as its threshold is exceeded, i.e., $v_{\rm bi} > 2v_{\rm A}$. Moreover, the growth rate of the kinetic instability is the largest when the beam velocity is $1 < v_{\rm bi}/v_{\rm A} < 2.5$, which implies that even if the drift velocity of the proton beam is very low, the kinetic instability can still effectively generate the ICWs in the solar wind. On the other hand, in the case of ICWs driven by electron beams, the results show that the kinetic instability has a negative or zero growth rate, which indicates that the electron beams cannot generate kinetic instability. Also, the reactive instability can be excited when its threshold $v_{\rm be} > 70v_{\rm A}$ is satisfied, implying that it is effective to excite ICWs by electron beams in the solar wind.

Thirdly, in view of the ubiquity and importance of α particles in the solar wind, we investigate the effect of α particles on the excitation mechanism of EMICWs. The results show that the real frequency, growth rate, and instability threshold of EMICWs are highly sensitive to the density and drift velocity of α particles. In particular, as the drift velocity of α particles increases, the growth rates of both ICWs and magnetosonic waves (MSWs) first decrease then increase, the effect on ICW is more significant. In addition, compared with the observations, the observed drift velocity of proton beams in the solar wind is usually less than

or close to the velocity threshold of EMICWs predicted by the theory. This indicates that both ion cyclotron and magnetosonic instabilities in the solar wind can effectively regulate the drift velocity of proton beams.

Finally, in order to examine the deceleration mechanism and evolution process of proton beams in the solar wind, we further investigate the effects of oblique ion cyclotron (OIC) and parallel magnetosonic (PMS) instabilities on the evolution of the proton beam in the solar wind. We also consider the effect of nonlinear wave particle interaction on beam deceleration, so as to establish the physical model of the evolution of proton beams in the solar wind. The results show that there are different instability excitation intervals between the OIC and the PMS. The OIC wave is more likely to grow at $\beta_{\mathrm{e}} < \beta_{\mathrm{e}}^{\mathrm{c}} \sim 0.5$, while the PMS wave tends to be excited at $\beta_{\mathrm{e}} > \beta_{\mathrm{e}}^{\mathrm{c}}$, where β_{e} is the ratio of electron thermal to magnetic pressure and $\beta_{\mathrm{e}}^{\mathrm{c}}$ is the critical value. As the solar wind streams away from the Sun, the OIC can be efficiently excited by proton beams, which constrains the beam velocity $v_{\mathrm{bi}}/v_{\mathrm{A}}$ below the instability threshold. However, when the solar wind exceeds the critical radius R_{c} (i.e. $R_{\mathrm{c}} > 0.55$ au), the PMS waves can be efficiently excited due to the lower threshold, and the proton beams continue to be decelerated by this instability. Moreover, the nonlinear wave-particle interaction can lead to a further deceleration of proton beams saturating at $v_{\mathrm{bi}}/v_{\mathrm{A}} \sim 1.2$. Therefore, these nonlinear wave-particle interaction can explain the observed results that the drift velocity of some proton beams in the solar wind is slightly greater than or close to the local Alfvén velocity. The present results may play an important role in understanding the deceleration mechanism and evolution of proton beams in the solar wind.